



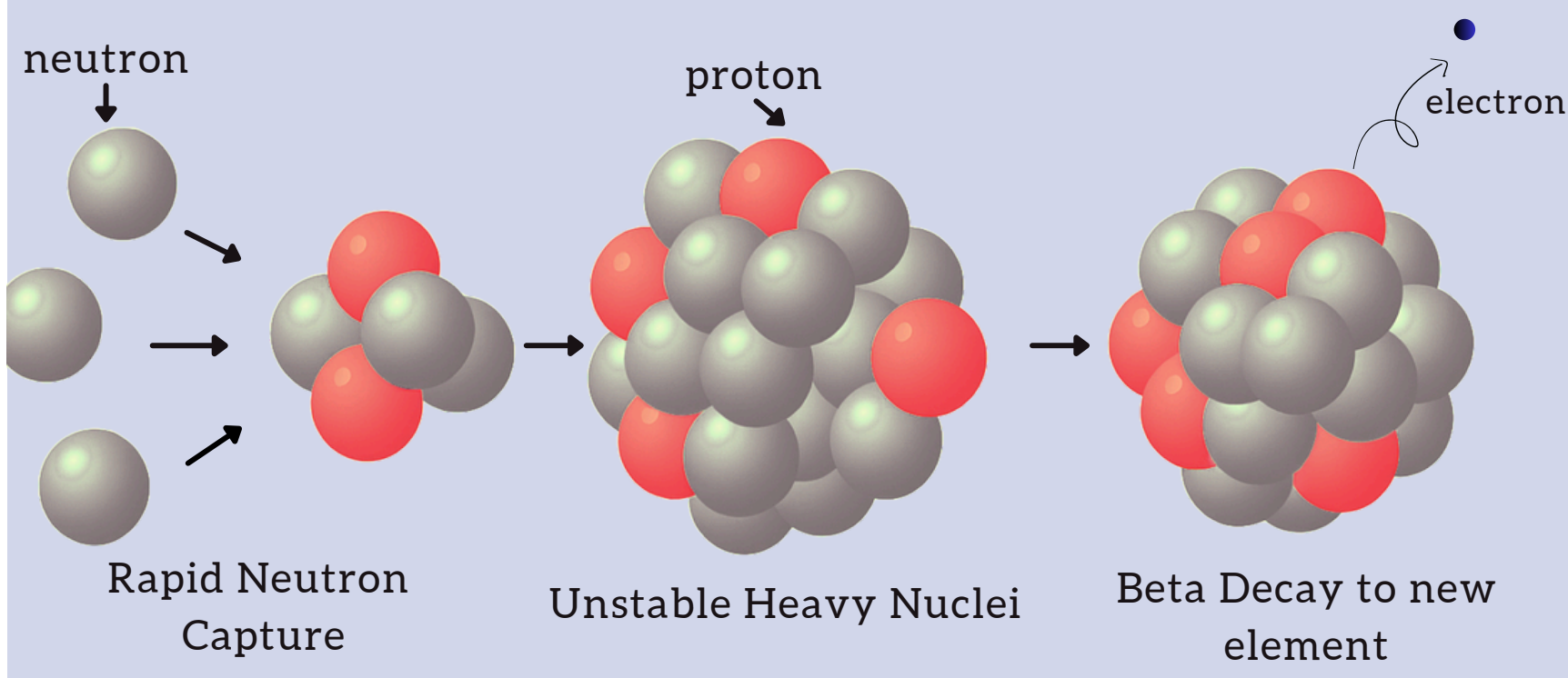
GRMHD SIMULATIONS OF BLACK HOLE-DISK SYSTEMS: HEAVY ELEMENT NUCLEOSYNTHESIS AND IMPLICATIONS FOR R-PROCESS SITES

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ABSTRACT

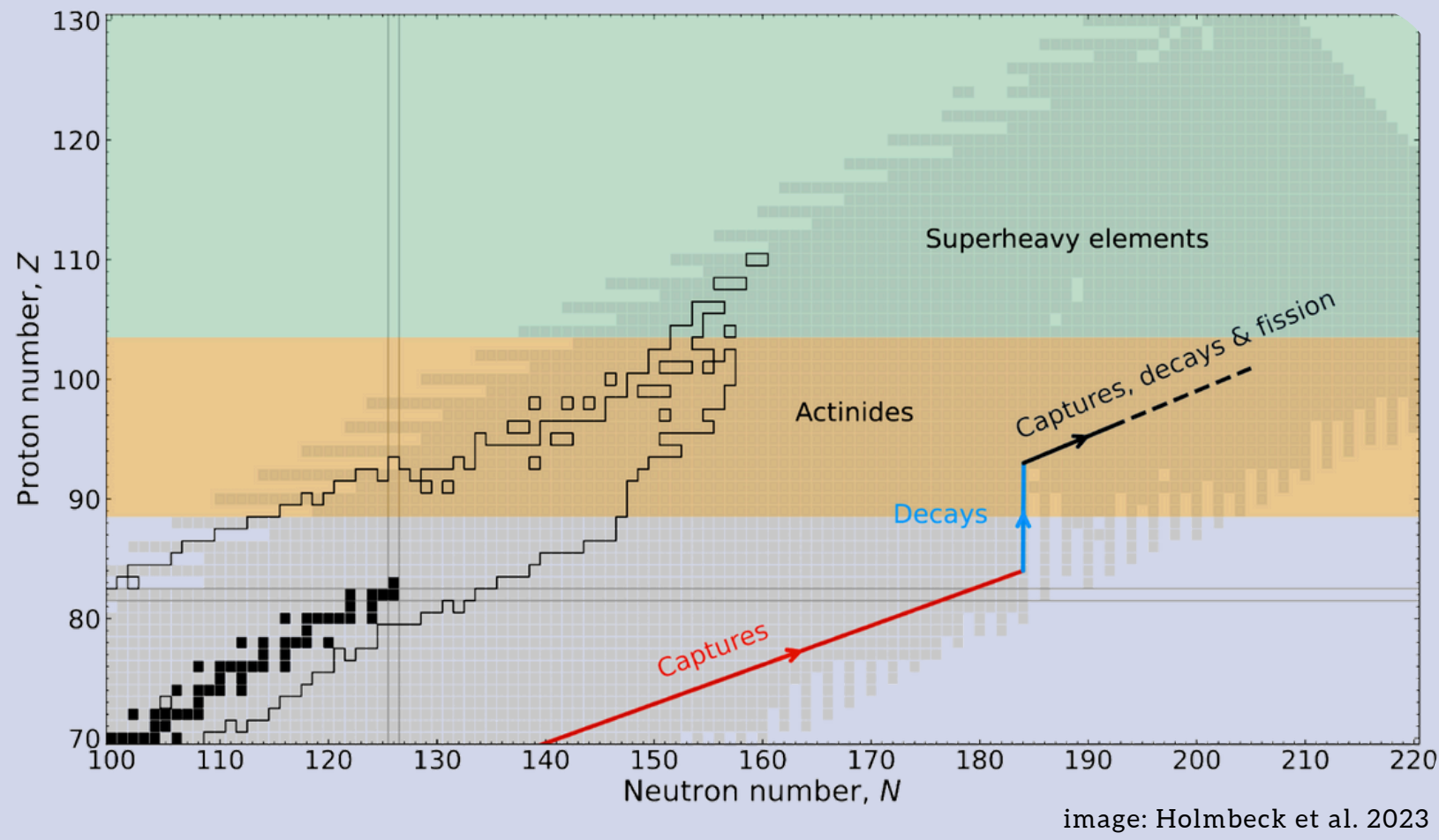
The astrophysical origin of heavy elements produced by the rapid neutron capture process (r-process) remains an open question. Compact objects, including neutron star mergers, collapsars, and magnetorotational supernovae, are potential r-process sites. We investigate black hole-accretion disk systems using general relativistic magnetohydrodynamic (GRMHD) simulations with the HARM-EOS code. Our simulations analyse how disk and black hole parameters affect neutron-rich outflows. Conditions extracted from these outflows are post-processed using the SkyNet nuclear reaction network to calculate detailed r-process abundances. Our results offer insights into heavy element nucleosynthesis, helping to clarify astrophysical sources of the universe's heaviest elements.

R-process nucleosynthesis - Astrophysical sites



- What is R-process
- Rapid neutron captures on seed nuclei in extreme conditions form heavy, neutron-rich elements.
 - Followed by β -decay, converting neutrons to protons and stabilizing nuclei into heavy elements.

- Figure (right panel) - r-process pathway and the dominant reaction channels active in the heavy-element region [black filled - stable | black outlined - measured | grey - theoretical]
- The r-process is responsible for forming about half of the elements heavier than iron (Fe) in the universe, including gold (Au), platinum (Pt), uranium (U), and thorium (Th).



Astrophysical Sites of the r-Process

- Binary Neutron Star Mergers: Robust site; confirmed by GW170817 + kilonova (AT2017gfo) [1]. Kilonovae are luminous transients powered by the radioactive decay of r-process elements
- Core-Collapse Supernovae: Neutrino-driven winds are often too proton-rich; role still debated.
- Collapsars & Magnetorotational SNe: BH + disk systems with strong magnetic fields; potential site for early-universe enrichment.

GRMHD - SIMULATION Code : HARM-EOS

(Black hole accretion with chemical composition changes)

- GRMHD Framework [2][3]:
 - Solves GRMHD equations in conservative form with finite-volume methods.

Core evolution equations:

- (continuity, energy - momentum conservation, induction equations)

$$\nabla_{\mu}(\rho u^{\mu}) = 0;$$

$$\nabla_{\mu} T^{\mu}_{\nu} = Q_{\nu};$$

$$\nabla_{\mu} F^{\mu\nu} = 0;$$

$$\partial_t U(\mathbf{P}) = -\partial_i \mathbf{F}^i(\mathbf{P}) + \mathbf{S}(\mathbf{P})$$

- Neutrino Cooling:
 - Leakage scheme[4] computes a gray optical depths for neutrinos ($v_e, v_{\bar{e}}, v_x$)
 - Q_{ν} - energy change due to neutrino cooling (in conservation equations)

- Equation of State (EOS)
 - Tabulated 3-parameter EOS: $\epsilon(\rho, T, Y_e)$ $P(\rho, T, Y_e)$

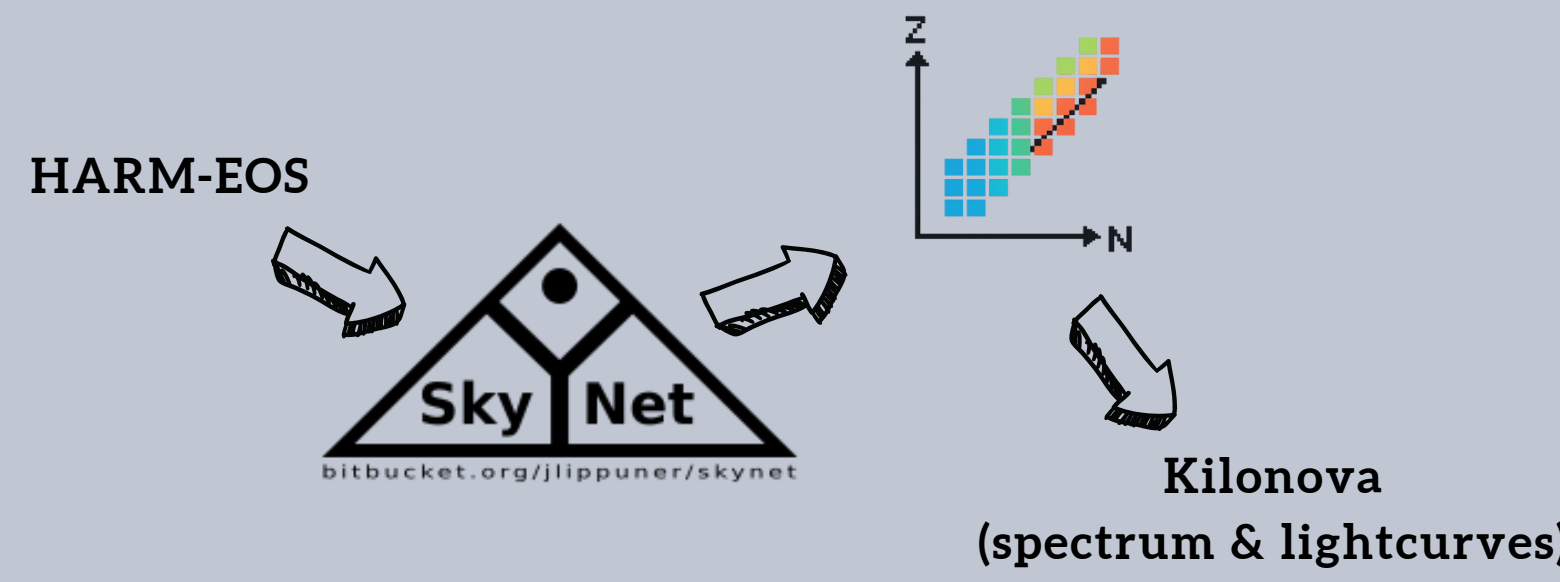
- Additional modules are available with self-gravity implementations

T^{μ}_{ν} - Stress-Energy Tensor, $F^{\mu\nu}$ - Faraday Tensor
U - conserved variables, P - Primitive variables, S - source term

Nuclear Reaction Network

Code : SKYNET

(Post processing of GRMHD results to calculate abundance profiles)

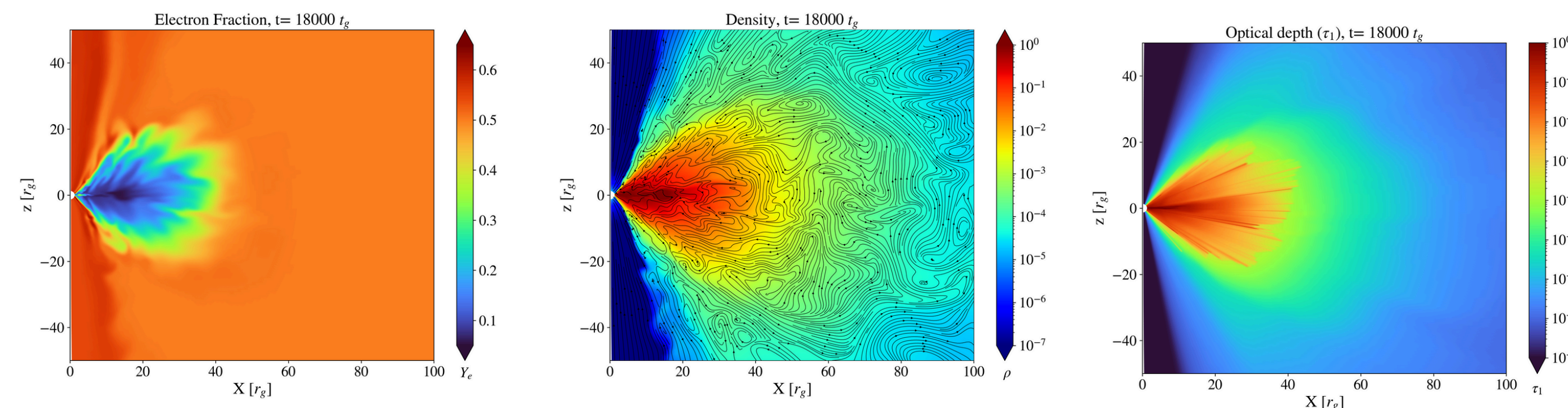


- Tracks >7 000 nuclides, ~140 000 reactions
- Accepts tracer histories $\rho(t)$, $T(t)$, $Y_e(t)$ from HARM-EOS
- Returns time-resolved abundances, heating rates
- Supports coulomb screening, self-heating & v -driven Y_e evolution

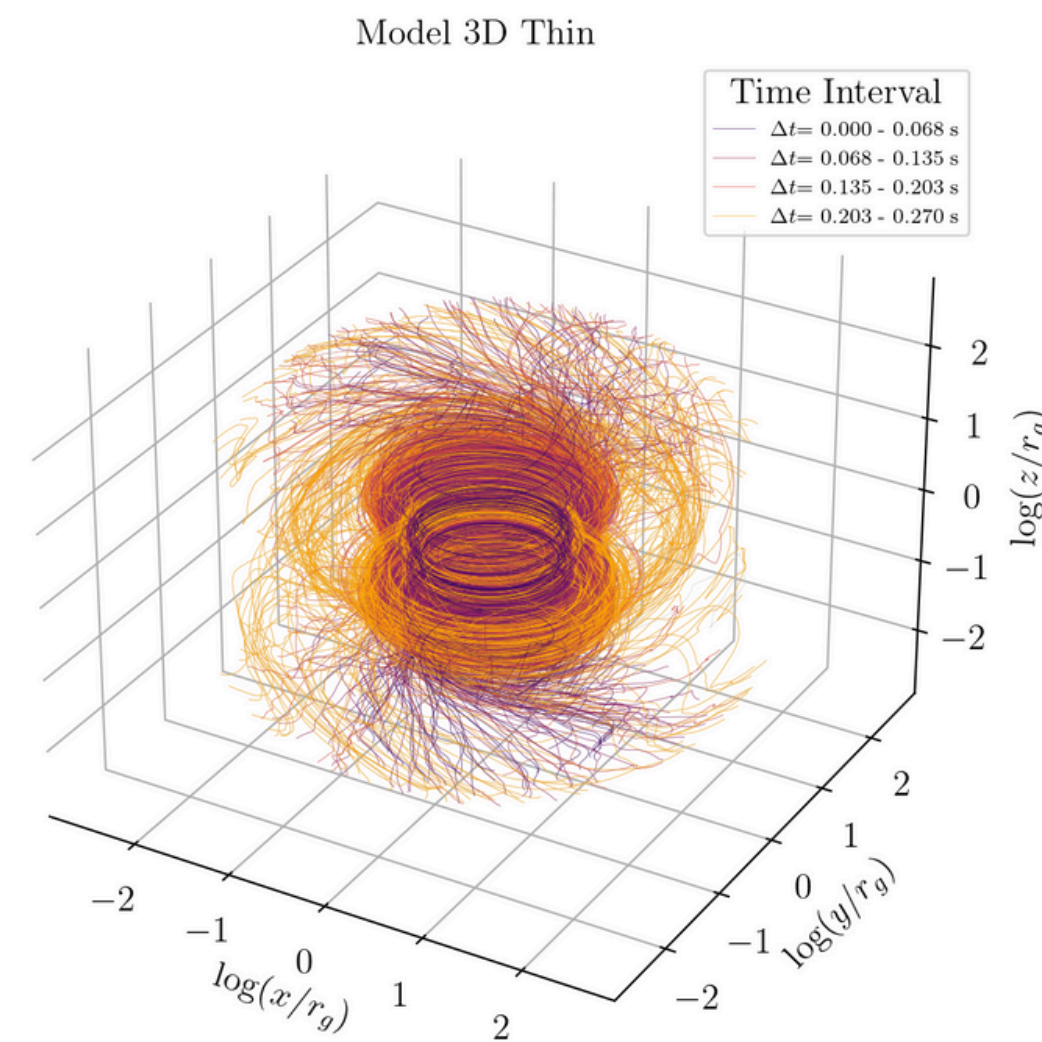
SkyNet [5] can be used to compute the nucleosynthesis evolution in all astrophysical scenarios where nucleosynthesis occurs. Proper elemental abundance combined with nuclear opacities are crucial for detailed studies of kilonova emission. Further radiation transport helps us study the EM emission following these events.

GRMHD Post-Merger Simulations

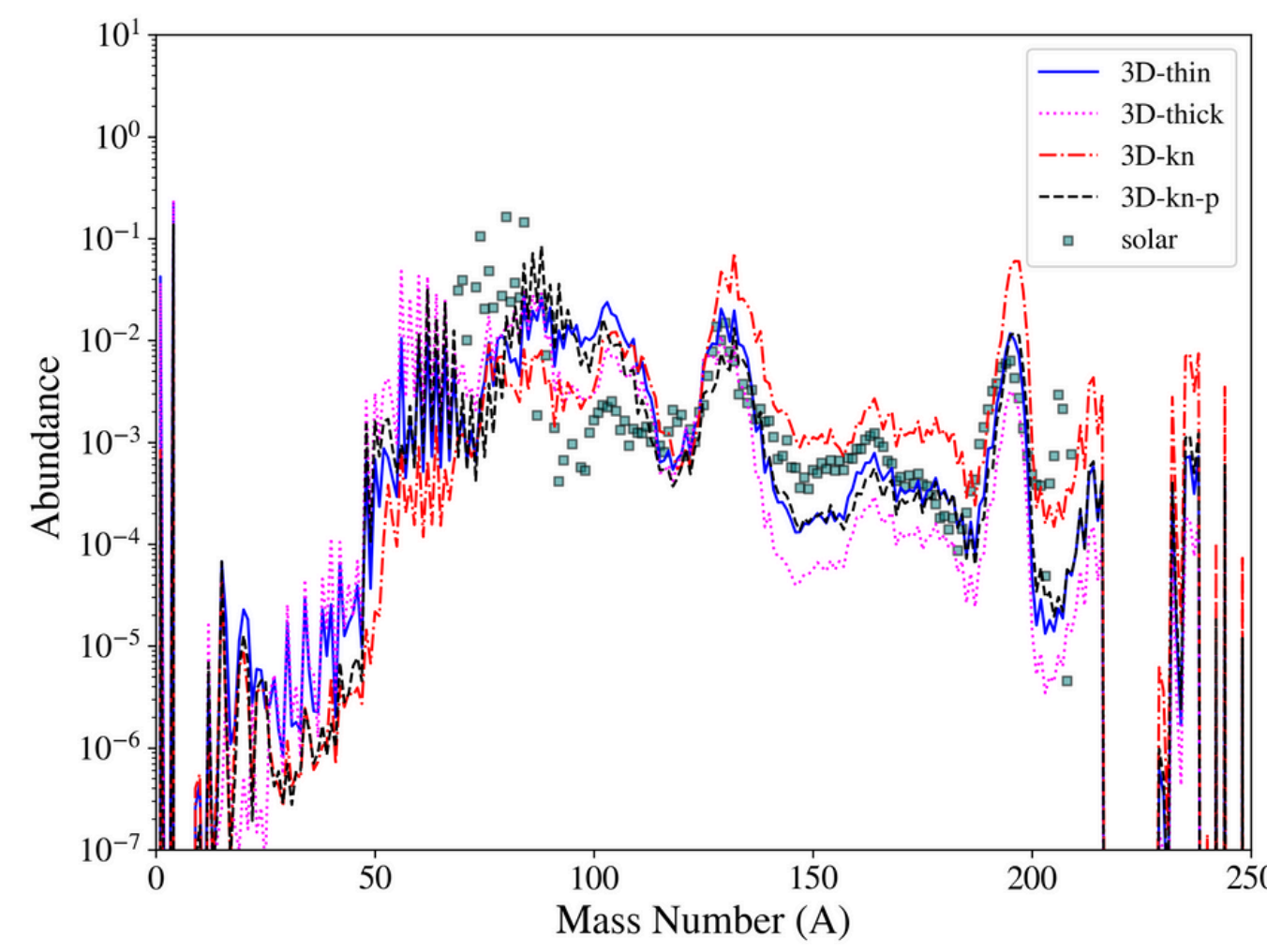
- 3-D v -GRMHD with HARM-EOS - composition-dependent, 3-parameter EOS + neutrino-leakage; resolves MRI turbulence, magnetised jet production, and self-consistent Y_e evolution.
- Simulation Parameters - BH spin $a = 0.6-0.9$, BH mass $3-8 M_{\odot}$, disk mass $\sim 0.001 - 0.1 M_{\odot}$, Poloidal B (plasma $\beta \sim 50 - 100$), disk entropy $7-10 k_B$ per baryon;
- The current simulation properties focus on the BNS and NS-BH merger scenario & some models are fine-tuned to reproduce kilonova emission followed by GRB211211A.
- $\sim 10^5$ tracers are initialised to follow unbound winds; record (ρ, T, Y_e) ; trajectories post-processed with SkyNet.



Accretion Disk snapshots at a later time of evolution
Left Panel: Electron Fraction, Mid Panel: Density + Magnetic field lines; Right Panel - Neutrino optical depth



Each Tracer particle records properties like density, temperature, electron fraction, coordinates & time to track the disk winds and used in SkyNet to calculate nuclear abundance



Nuclear Abundance profiles of four 3D models in this work.
Models succeed in reproducing solar r-process peaks ($A \sim 130, 195$).

Insights into CCSNe r-Process

"Ordinary" CCSNe $\neq$ heavy r-process

- Standard neutrino-driven explosions synthesise only light trans-iron nuclei [6]; full $A \gtrsim 130$ production needs strong magnetic fields or BH accretion disks

Collapsar & MHDsNe $\approx$ merger disks

- Neutrino-cooled, MRI-turbulent BH-disk systems in **collapsars**[7] show the same low- Y_e thermodynamics we capture in post-merger runs—hence they can, in principle, eject comparable or even larger r-process masses.
- Multiple simulations [8][9] have presented evidence of a moderate amount of heavy r-process nuclei formation from **magnetorotationally driven supernovae**, highlighting the role of CCSNe in heavy element production in the universe.

New collapsar simulations -

- HARM-EOS engine [Future Plans]: fully 3-D GRMHD + tabulated EOS microphysics + neutrino-leakage and new self-gravity module—validated on neutron-star merger disks, can be used to extend the studies to collapsar BH-disk studies

Conclusion

- 3D simulations of post merger accretion disks with multiple initial configurations were carried out using the new HARM-EOS 3D v -GRMHD code, developed at CTP PAS.
- Post-processing using SkyNet nuclear reaction network shows that disk winds robustly produce heavy r-process ($A \gtrsim 100$); yields ($10^{-3}-10^{-2} M_{\odot}$) of ejecta. Results match solar abundance profile, and the velocity/ejecta properties are consistent with powering a GW170817-like kilonova.
- Further prospects of studying r-process from CCSNe are discussed, as collapsars are one of the leading candidates for heavy element production in the universe.

References

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